Upper Ocean Heat Content Variability in the Pacific Ocean

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論 文 内 容 要 旨

In order to understand climate changes of the earth, numerous studies on sea surface temperature (SST) and atmospheric anomaly fields have been done so far. In the Pacific Ocean, a lot of observational studies have improved our knowledge of variabilities of SST and atmospheric anomaly fields related to El Niño/Southern Oscillation (ENSO) phenomenon, and to low-frequency climate variability with longer timescale than ENSO. However, the physical mechanisms of ENSO and the low-frequency variability are still unclear at the present time.

Studies on numerical model experiments have also been done to explain physical mechanisms of ENSO and the low-frequency variabilities. During the past decade, a lot of hypotheses for both ENSO and the low-frequency variabilities have been proposed. All of them have suggested that the upper ocean heat content (OHC) anomaly plays an important role as well as SST and atmospheric anomaly fields for both ENSO and the low-frequency variabilities, although behaviors of the OHC anomaly in the proposed hypotheses are different from each other. Therefore, it is meaningful to analyze OHC anomaly field in order to check and improve the various hypotheses and obtain new findings of ENSO and the low-frequency variabilities.

However, the lack of the datasets for upper ocean temperature at basin scale did not allow us to analyze the OHC variabilities related to the ENSO and the low-frequency variabilities before the late 1980s. Since the early 1990s, upper ocean temperature datasets at basin or global scales and with long time length (about 50 years) have been prepared, and observational studies on OHC anomaly field have been done. However, detailed information on OHC behaviors related to the ENSO and the low-frequency variabilities has not been provided adequately so far. The purpose of this thesis is to analyze OHC anomaly fields in the Pacific Ocean and describe the variability of OHC anomaly field. In addition, relationships between OHC, SST and atmospheric anomalies, and relationships between ENSO-scale variability and the low-frequency variability are also explored in this thesis.

In Chapter 2, OHC anomaly fields in the Pacific Ocean from 30°S to 60°N over a 45-year period are analyzed with special reference to their relationship with ENSO events. In the present study, for convenience, the OHC is defined as vertically averaged temperature from the sea surface to 300 m depth. Based on a cluster analysis, it is found that interannual variability with a period of 3-6 years is dominant in the eastern and western tropical Pacific,

while longer-timescale variability with a period of about 10 to 20 years (hereinafter, we call this timescale as "decadal scale") is dominant in the central equatorial Pacific and mid to high latitudes.

In order to focus our attention on the relationship between OHC anomalies and ENSO events, 3-6 year variations are extracted by a band-passed filtering with half power points at 3- and 6-year periods. The result clearly shows the cyclic and anticlockwise propagation of OHC anomalies on the circuit in the northern tropical Pacific. That is, an eastward propagation along the equator, a northward propagation at the eastern boundary, a westward propagation along the latitudinal belt centered around 16°N and a southward propagation at the western boundary are found. The westward propagating OHC anomaly along 16°N is enhanced in the west of the International Date Line (hereinafter, we call the region as "WTP") after mature phase of ENSO events.

The OHC anomaly spatially averaged over the entire equatorial Pacific from 4° N to 4° S leads the Niño-3 index by two seasons (i.e., six months), which is approximately a quarter of the ENSO period or a little bit shorter. In addition, it is also found that the OHC anomaly in the entire equatorial Pacific is decreasing when the Niño-3 index is positive, while that in higher latitudes, from 5°N to 20°N, in the tropical North Pacific is increasing at the same time. This fact indicates the exchange of an OHC anomaly between the equatorial Pacific and higher latitudes, and supports the "recharge oscillator" model for the ENSO dynamics. Further, it is shown that the magnitude of the OHC anomaly of the entire equatorial Pacific is directly related to that of the subsequent (two seasons or more later) Niño-3 index, which means that the larger amplitude of the OHC anomaly in the entire equatorial Pacific corresponds to the larger magnitude of the subsequent ENSO event, although there exists an asymmetry between the preceding positive and negative OHC anomalies and the subsequent Nino-3 index. These facts strongly confirm the previous findings based on observations and numerical models. It is also shown that after the 1976/77 regime shift, magnitudes of the OHC anomalies related to ENSO become greater, and an asymmetric feature between the preceding positive and negative OHC anomalies and the subsequent Niño-3 index is exaggerated.

In Chapter 3, various datasets for the period of 45 years from 1955 to 1999 are analyzed in order to investigate an air-sea interaction in the WTP region, where OHC anomalies are enhanced after a mature phase of ENSO events as described in Chapter 2. It is found that OHC anomalies in the WTP region are amplified by an anomalous wind stress curl (WSC) in the WTP after a mature stage of ENSO event. This suggests that an air-sea interaction is taking place in the WTP. This air-sea interaction is participated by OHC anomaly propagating westward along the latitudinal belt from 10°N to 20°N, SST, sea level pressure (SLP) and WSC.

It is shown that when positive (negative) OHC anomalies propagating westward off equator from the eastern North Pacific reach the WTP after a warm (cold) event of ENSO, positive (negative) SST anomalies immediately appear there, although OHC does not directly relate to SST in the eastern North Pacific. Then large negative (positive) SLP and accompanying positive (negative) WSC anomalies cause the decreasing (increasing) tendency of OHC anomalies in the WTP. Further, it is shown that these relationships occur with a linear relationship in their amplitudes. That is, as the amplitudes of the OHC, SST, SLP and WSC anomalies become larger, the amplitudes of SST, SLP, WSC and tendency of OHC anomalies also become larger respectively.

In Chapter 4, decadal-scale variability of OHC in the tropical Pacific is investigated and compared with that of ENSO scale. It is found that the decadal-scale OHC anomaly with a period of about 13 years also shows anticlockwise propagation in the tropical North Pacific like as that of ENSO scale described in Chapter 2. It is also shown that the entire equatorial OHC anomaly leads Niño-3 index anomaly by about a quarter (about 3 years) of the period of the decadal variability in the tropical Pacific. This time lag of a quarter of the period is consistent with the idea of the recharge oscillator model for ENSO dynamics. Furthermore, it is shown that the magnitude of leading

OHC anomalies in the entire equatorial Pacific is linearly related to the subsequent magnitudes of Niño-3 and Niño-3.4 indices. This relationship is also similar with that of ENSO scale shown in Chapter 2, but there are several different points between them. Particularly, in contrast with the ENSO scale, the amplitude is larger in the central equatorial Pacific (Niño-3.4 region) than in the eastern region (Niño-3 region) as suggested by the results of cluster analyses described in Chapter 2.

In the eastern equatorial Pacific, SST and zonal wind stress anomalies lag the OHC anomaly at the decadal scale, while they are almost in phase at ENSO scale, which means that effect of an air-sea interaction for growing OHC anomalies at the decadal scale is weaker than ENSO scale. This may be the reason for the weak signal of the eastern equatorial OHC anomalies at the decadal scale. In the WTP region, the westward propagating OHC anomalies at the decadal scale are enhanced as well as ENSO scale. However, the correlation coefficients of WSC anomaly versus temporal changing rates of the OHC anomaly in the WTP at the decadal scale are smaller than that of ENSO scale. The result shows that correlation coefficients of latent heat flux and temporal changing rates of OHC anomalies in the WTP at the decadal scale are larger than that of ENSO scale, which suggests that, in contrast with ENSO scale, anomalous latent heat flux has an important role in the OHC variations in the WTP rather than WSC at the decadal scale.

In addition, the relationships between the decadal-scale and ENSO-scale variabilities of OHC, SST and SLP anomalies in the tropical Pacific are explored. The results show that the amplitudes of OHC, SST and SLP anomalies in the eastern equatorial Pacific (the Nino-3 region) are larger during the period when the decadal-scale OHC anomalies in the eastern equatorial Pacific are negative. Further, anticlockwise propagation of OHC anomalies in the tropical Pacific and the recharge oscillator-like behavior at ENSO scale described in the Chapter 2 are clearly seen during the same period.

In the WTP region, it is shown that the relationships among OHC, SST, SLP and WSC in the WTP described in Chapter 3 are robust, and their amplitudes are enhanced in the early 1970s, the mid 1980s and the late 1990s. In these periods, SST anomalies at the decadal scale are positive in the WTP. These facts suggest that the decadal-scale variations in the tropical Pacific might cause the decadal fluctuations of ENSO-scale variability of OHC and other variables in the eastern equatorial Pacific and in the WTP region.

In Chapter 5, OHC anomaly field in the Pacific basin from 1955 to 1999 is analyzed to investigate its relationship to the Aleutian Low (AL) and the Kuroshio transport (KT) in the sea south of Japan, at the multidecadal timescale of a period longer than 30 years. It is found that OHC anomaly circulates clockwise in the North Pacific subtropical gyre. Lag correlation analyses between the North Pacific Index (NPI), which is a good indicator of activity of the AL, the KT and OHC anomaly, suggest that the clockwise propagation of OHC anomaly closely links to an activity of the AL and a variation of the KT. After about five years since the AL is intensified, the KT starts increasing, and after further five years, OHC anomaly in the Kuroshio Extension region does increasing.

Furthermore, lag correlation analyses between various oceanic and atmospheric variables also suggest that the clockwise propagation of OHC anomaly in the subtropical gyre is produced from an air-sea interaction over the North Pacific. That is, positive OHC anomaly in the Kuroshio Extension region leads positive SST anomaly there, which is succeeded by the weakening of the AL. Further, the weakened AL, equivalently the weakened WSC over the central part of the subtropical gyre, causes the decreasing tendency of the OHC anomalies in the southwestern subtropical gyre through the spin-down process of the subtropical gyre. The positive OHC anomaly in the Kuroshio Extension region, in turn, is replaced by the negative OHC anomaly propagating clockwise from the southwestern subtropical gyre. Then negative SST anomaly appears in the east of Japan, and the same process with a sign reversed evolves. This sequential process strongly supports the hypothesis proposed by Latif and Barnett (1996) regarding the low-frequency variability in the North Pacific.

In Chapter 6, the conclusions of the present thesis are given. The results not only support the hypotheses and results of numerous model experiments provided in the early works, but also point out new findings of OHC variabilities at ENSO, the decadal and multidecadal timescales. Further, relationships between OHC, SST and atmospheric anomaly fields and relationships between ENSO- and the decadal-scale variabilities in the Pacific Ocean are explored in the present thesis. These results suggest that the analyses of OHC anomaly are very important and meaningful for deeper understanding of the climate changes in the Pacific and other basins.

論文審査の結果の要旨

気候変動メカニズムの解明のためには，海の役割を知ることが重要である。これまで，海面水温場に対する解析は行われているものの，表層の貯熱量（以下，OHC）を対象とした研究は，データセットの問題もあり，極めて少数で，研究対象海域も限られていた。いっぽう，最近，数値モデル実験などから，OHCの振る舞いの考察がメカニズム解明に重要であることが示唆されている。このような背景のもとで長谷川拓也提出の論文は，これまで詳細な解析がなされていない太平洋におけるOHCの変動特性について調べることを目的としたものである。

まず，3-6年の周期を持つエルニーニョ/南方振動現象イベント（ENSO）に関係するOHCの変動特性を調べた。その結果，ENSOに関係してOHC偏差が北太平洋熱帯域を反時計回りに伝播する様子が見出された。また，エルニーニョ期間中には赤道域全体のOHCが減少傾向にあることも示され，さらに，太平洋全体にわたる貯熱量データの解析から，赤道域とより高緯度帯の間で行われる貯熱量の交換が，南半球よりも北半球で卓越するという新しい知見を得た。

次に，ENSOに関係して北緯15度付近を西進するOHC偏差が，日付変更線の西側の領域（以下,' WTP'）で振幅が強化する原因について調べた。その結果，WTPにおいて，ENSOに関係して，OHC，海面水温，大気場が正のフィードバック回路を構成していることがわかった。WTPの東側の海域では，このような特徴が見られない。これは，WTPにおける大気海洋相互作用がENSO現象に重要であることを示唆する。

さらに，赤道域の10年スケールのOHC変動について調べた。このスケールにおいても，ENSOスケールのOHC変動とよく似たOHC偏差の半時計回り伝播特性などが見出された。また，10年スケールのOHC偏差の符号と，ENSOスケールのOHC変動の間に関係が見られた。すなわち，10年スケール変動のOHCが東部赤道域で負のとき，より振幅の大きいENSOイベントが発生していることがわかった。

太平洋中・高緯度では，30年以上の周期帯におけるOHC変動が卓越していることがわかった。この周期帯でも，北太平洋中緯度において時計回りのOHC偏差の伝播が見出された。この伝播とアリューシャン低気圧，黒潮流量，北太平洋亜熱帯モード水そして日本東方海域の海面水温の間に，振動現象を作り出す関係があることを見出した。

以上のように本論文は，OHCを主体とする解析によって，海面水温場などの解析では知ることができない海洋内部の変動を捉え，観測に基づく新しい多くの知見を得，さらに過去の数値モデル実験結果の検証を行ったものであり，本人が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって，長谷川拓也提出の博士論文は，博士（理学）の学位論文として合格と認める。